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Application of Computational Fluid Dynamics to a Preliminary Extended Area Protection System (EAPS) Projectile

by Karen Heavey and Jubaraj Sahu

ARL-MR-649 September 2006

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Application of Computational Fluid Dynamics to a Preliminary Extended Area Protection System (EAPS) Projectile

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14. ABSTRACT

Computational fluid dynamics approaches were used to compute the flow fields and aerodynamic forces and moments of a slender-body finned projectile. Steady-state numerical results have been obtained for a series of cases, with Mach numbers ranging from 1.5 to 5.0 and at angles of attack from 0° to 5°. Full three-dimensional computations were performed using a cubic k-epsilon turbulence model. In general, the computed aerodynamic coefficients compared well with available semi-empirical data.

15. SUBJECT TERMS

baseline, finned projectile, low angle of attack, computational fluid dynamics

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1. Introduction

The prediction of aerodynamic coefficients for projectile configurations is essential in assessing the performance of new designs. Accurate determination of aerodynamics is critical to the low-cost development of new advanced guided projectiles, rockets, missiles, and smart munitions. Fins, canards, and jets can be used to provide control for maneuvering projectiles and missiles. The flow fields associated with these control mechanisms for the modern weapons are complex, involving three-dimensional (3-D) shock-boundary layer interactions and highly viscous dominated separated flow regions (*1–5*). Computational fluid dynamics (CFD) has emerged as a critical technology for the aerodynamic design and assessment of weapons. Improved computer technology and state-of-the-art numerical procedures enable solutions to complex, 3-D problems associated with projectile and missile aerodynamics. In general, these techniques have the potential to produce accurate and reliable numerical results for complex projectile and missile configurations.

As part of a U.S. Army Advanced Technical Objective (ATO) for Extended Area Protection System (EAPS), technologies are currently being developed to support future air defense system. The goal for the air defense system is to leverage the best combination of directed energy and/or kinetic energy (KE) capabilities against the aerial threat and achieve the capability to protect the force and high value assets against incoming rockets, artillery, and mortars. Improved lethality, accuracy, and fire control are required for a KE munition-based weapon. Various system technologies are being developed under this ATO to address these issues. Critical technologies that are required to bridge the gap will support enhanced lethality, effective fire control, increased engagement kill probability, and simultaneous engagements of multiple threats. High-fidelity CFD is required in the design process to achieve optimized location of jet and/or other control devices for increased maneuverability of a projectile or a missile. This approach has shown great promise for the optimization and strategic location to achieve the turning force necessary to terminally steer a missile or projectile to its target, thereby increasing the lethality of future combat systems. The first step in the design process is to be able to obtain the full aerodynamics of the projectile. This report presents the results of computational investigation of the aerodynamics of a preliminary EAPS projectile design configuration to be used as a test-bed for electronics development and aerodynamic control authority being developed.

The information presented in this report focuses on the application of CFD to a preliminary design for the EAPS configuration—a slender-body finned projectile. A description of the computational techniques is presented, followed by a description of the applications of these techniques to the computational model. Computed results for the initial configuration are presented for Mach numbers ranging from 1.5 to 5.0 at angles of attack ranging from 0° to 5°. The computed data are compared with semi-empirical data provided by Arrow Tech (*6*).

2. Solution Technique

2.1 CFD++ Flow Solver

A commercially available code, CFD++ (*7*, *8*), is used for the numerical simulations. The basic numerical framework in the code contains unified-grid, unified-physics, and unified-computing features. The user is referred to these references for details of the basic numerical framework. Here, only a brief synopsis of this framework and methodology is given.

The 3-D, Reynolds-averaged Navier-Stokes (RANS) (*9*) equations are solved using the following finite volume method:

$$\frac{\partial}{\partial t}\int_V \mathbf{W} dV + \oint \left[\mathbf{F} - \mathbf{G}\right] \cdot dA = \int_V \mathbf{H} dV , \tag{1}$$

where W is the vector of conservative variables, F and G are the inviscid and viscous flux vectors, respectively, H is the vector of source terms, *V* is the cell volume, and *A* is the surface area of the cell face.

The numerical framework of CFD++ is based on the following general elements: (1) unsteady compressible and incompressible Navier-Stokes equations with turbulence modeling (unified-physics), (2) unification of Cartesian, structured curvilinear, and unstructured grids, including hybrids (unified-grid), (3) unification of treatment of various cell shapes including hexahedral, tetrahedral and triangular prism cells (3-D), quadrilateral and triangular cells (two-dimensional) and linear elements (one-dimensional) (unified-grid), (4) treatment of multiblock patched-aligned (nodally connected), patched-nonaligned, and overset grids (unified-grid), (5) total variation diminishing discretization based on a new multi-dimensional interpolation framework, (6) Riemann solvers to provide proper signal propagation physics, including versions for preconditioned forms of the governing equations, (7) consistent and accurate discretization of viscous terms using the same multi-dimensional polynomial framework, (8) pointwise turbulence models that do not require knowledge of distance to walls, (9) versatile boundary condition implementation includes a rich variety of integrated boundary condition types for the various sets of equations, and (10) implementation on massively parallel computers based on the distributed-memory message-passing model using native message-passing libraries or Message-Passing Interface, Parallel Virtual Machine, etc. (unified computing).

The code has brought together several ideas on convergence acceleration to yield a fast methodology for all flow regimes. The approach can be labeled as a “preconditioned-implicit-relaxation” scheme. It combines three basic ideas: implicit local time-stepping, relaxation, and preconditioning. Preconditioning the equations ideally equalizes the eigen values of the inviscid flux Jacobians and removes the stiffness arising from large discrepancies between the flow and

sound velocities at low speeds. Use of an implicit scheme circumvents the stringent stability limits suffered by their explicit counterparts, and successive relaxation allows update of cells as information becomes available and thus aids convergence.

2.2 Numerical Technique

The cubic k-ε turbulence model was selected for this study. A pressure-temperature based inflow/outflow routine was utilized for the inflow boundary condition, while a characteristics-based inflow/outflow routine was used for the farfield boundary condition. A centroidal extrapolation routine was used for the outflow boundary and an isothermal wall condition was used on the projectile surfaces. All calculations were performed under atmospheric conditions of P_o = 101325 Pa and T_o = 298 K.

All computations were performed on the IBM SP-4 at the U.S. Army Research Laboratory Major Shared Resource Center. Most of the cases were completed utilizing 16 processors per run and averaged 100 CPU hours to converge. The next section describes the model geometry, computational mesh, and the flow conditions.

3. Model Geometry and Numerical Grid

3.1 Projectile Model and Geometry

The geometric model for the preliminary design is a blunt-nosed, ogive-cylinder projectile with tail fins. The length of the projectile is 316.7 mm, with a body diameter of 23.5 mm. There are four tail fins on the aft end of the missile, aligned with the base of the projectile. The computational model is shown in figure 1.

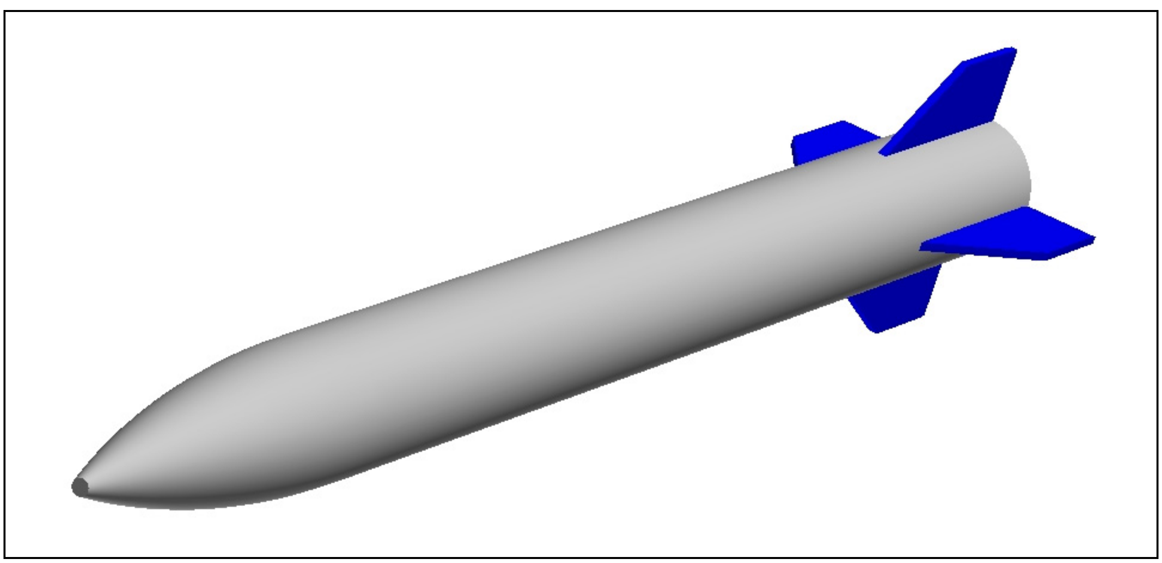

Figure 1. Computational model of a preliminary EAPS projectile configuration.

3.2 Computational Mesh

The grids for this study were created using GRIDGEN (*10*), a commercially available software package. The computer-aided design (CAD) file supplied by Arrow Tech Associates was imported to provide the basic geometry. A structured hexahedral mesh was created, using a variable blocking strategy. The first grid consisted of 2.2-million hexahedral cells, with the outer boundary extending out approximately two body lengths. After several preliminary computations, it was apparent that a second grid would be necessary for the lower Mach number cases. An extra layer of cells was added at the outer boundary, extending the perimeter of the grid to four body lengths. Figure 2a shows the surface grid in the aft region of the missile and figure 2b shows both the symmetry plane and a circumferential cut in this region. A view of the grid in the symmetry plane, showing the outer layer added for the lower Mach number cases, is shown in figure 3. In each case, the resultant grid was exported in the code-specific unstructured format required by CFD++.

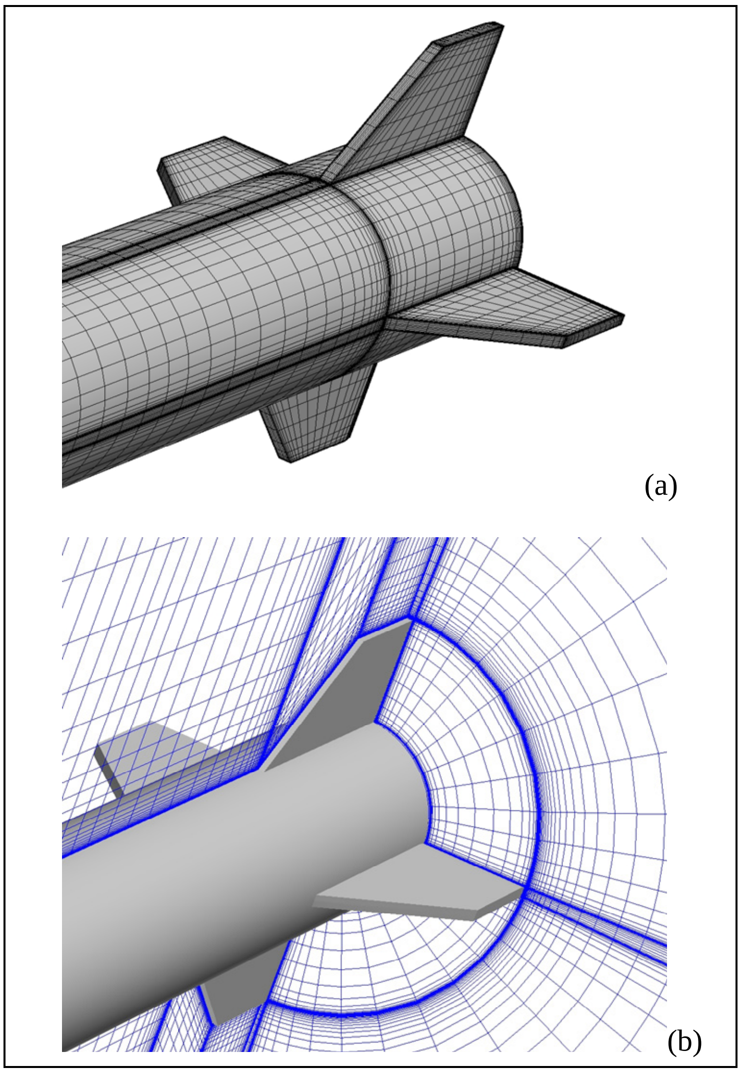

Figure 2. Expanded view of aft portion of the computational mesh: (a) surface and (b) axial and circumferential.

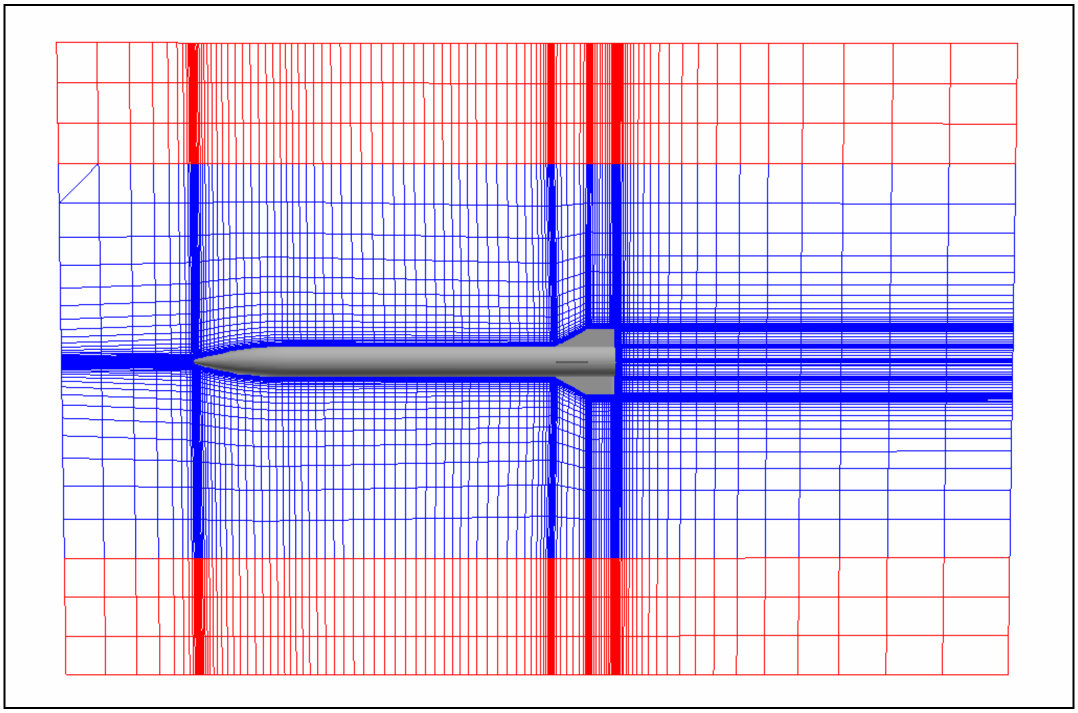

Figure 3. View of the extended grid (symmetry plane).

4. Results and Discussion

Computations using viscous Navier-Stokes methods were performed to predict the flow field and aerodynamic coefficients for a slender-body finned projectile, using the CFD++ flow solver for a range of Mach numbers (from 1.5 to 5.0) at low (0°, 2°, and 5°) angles of attack. Full 3-D calculations were performed, and no symmetry was used. The computational results are compared to available semi-empirical data.

4.1 Qualitative Results

Figure 4 shows surface pressure contours for a the computed solution for the Mach 3.5, alpha 2° case. The high pressure shown on the nose and leading edge of the fins is typical.

The following series of figures show pressure and Mach contours in the symmetry plane for selected Mach numbers and angles of attack. Figures 5–7 show pressure contours for Mach numbers 1.5, 3.5, and 4.85. As the angle of attack increases from 0° to 5°, the pressure contours change around the nose and fin areas of the projectile. The magnitude of the pressure changes as the Mach number increases. Similar characteristics are seen in the Mach contours shown in figures 8–10. Again, the most apparent changes are in the nose and fin areas of the flow field.

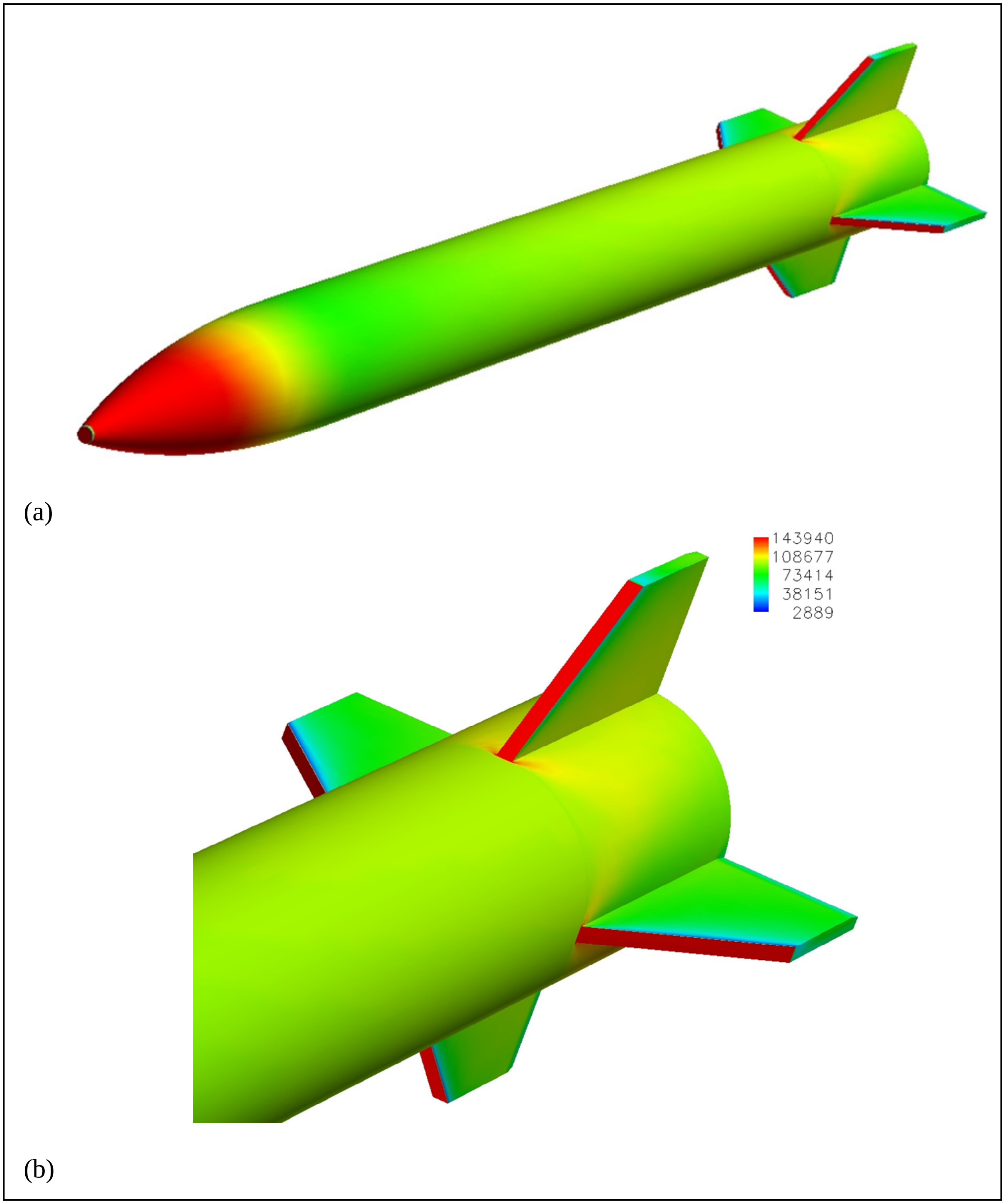

Figure 4. Surface pressure contours (in pascals) for Mach 3.5, alpha = 2°: (a) full view and (b) expanded view.

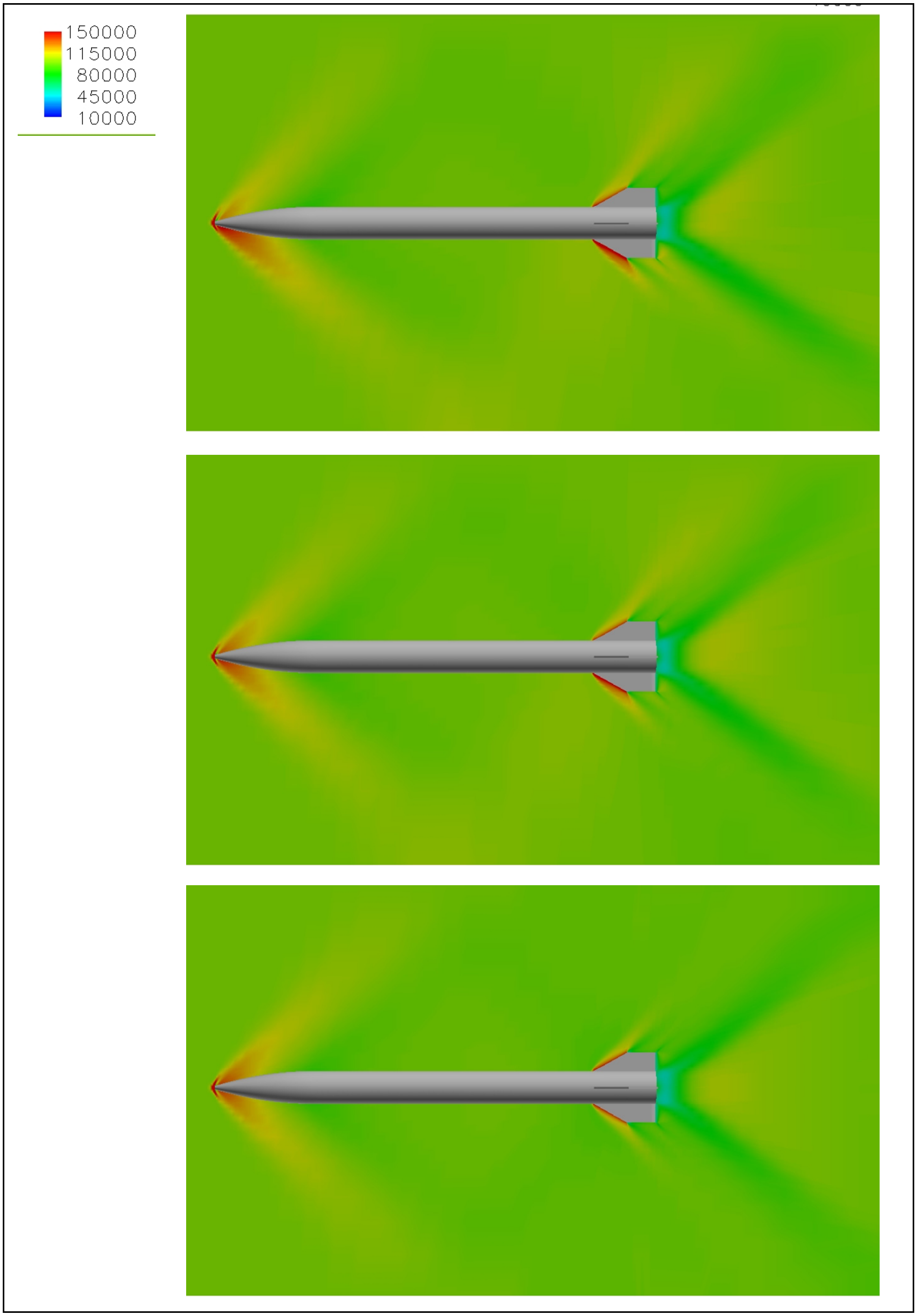

Figure 5. Pressure contours (in pascals) for Mach number 1.5, alpha 0°, 2°, and 5° (bottom to top).

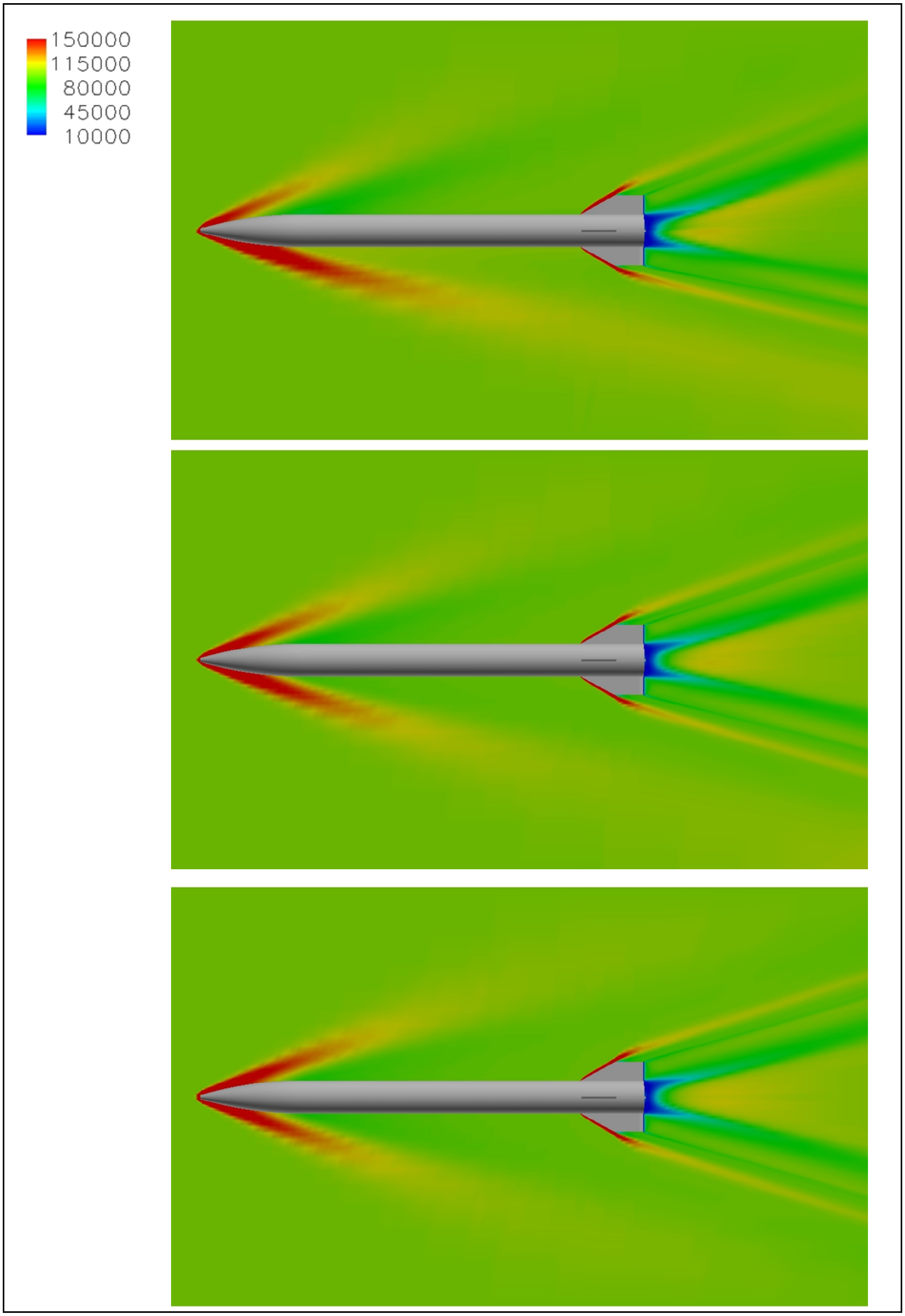

Figure 6. Pressure contours (in pascals) for Mach number 3.5, alpha 0°, 2°, and 5° (bottom to top).

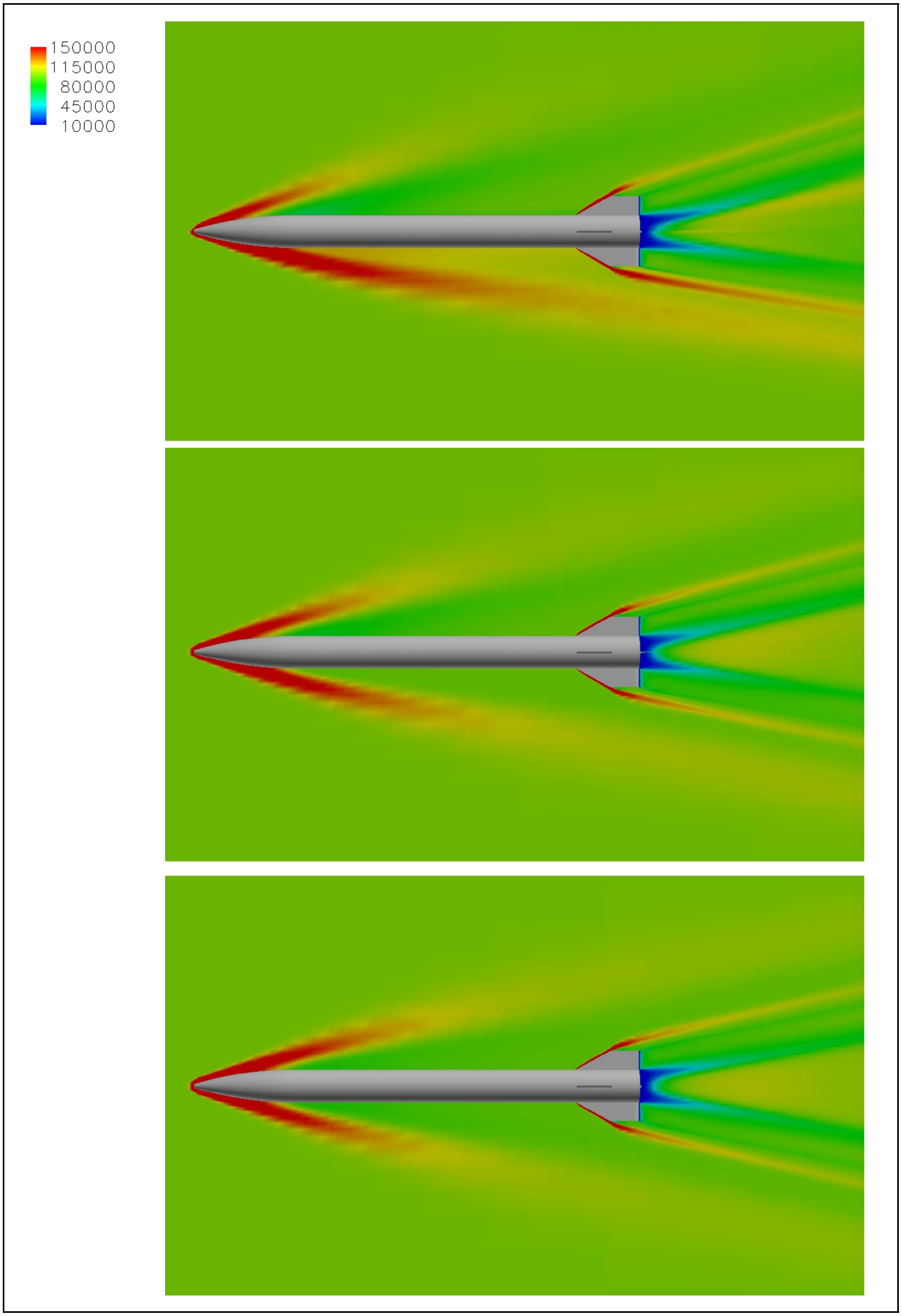

Figure 7. Pressure contours (in pascals) for Mach number 4.85, alpha 0°, 2°, and 5° (bottom to top).

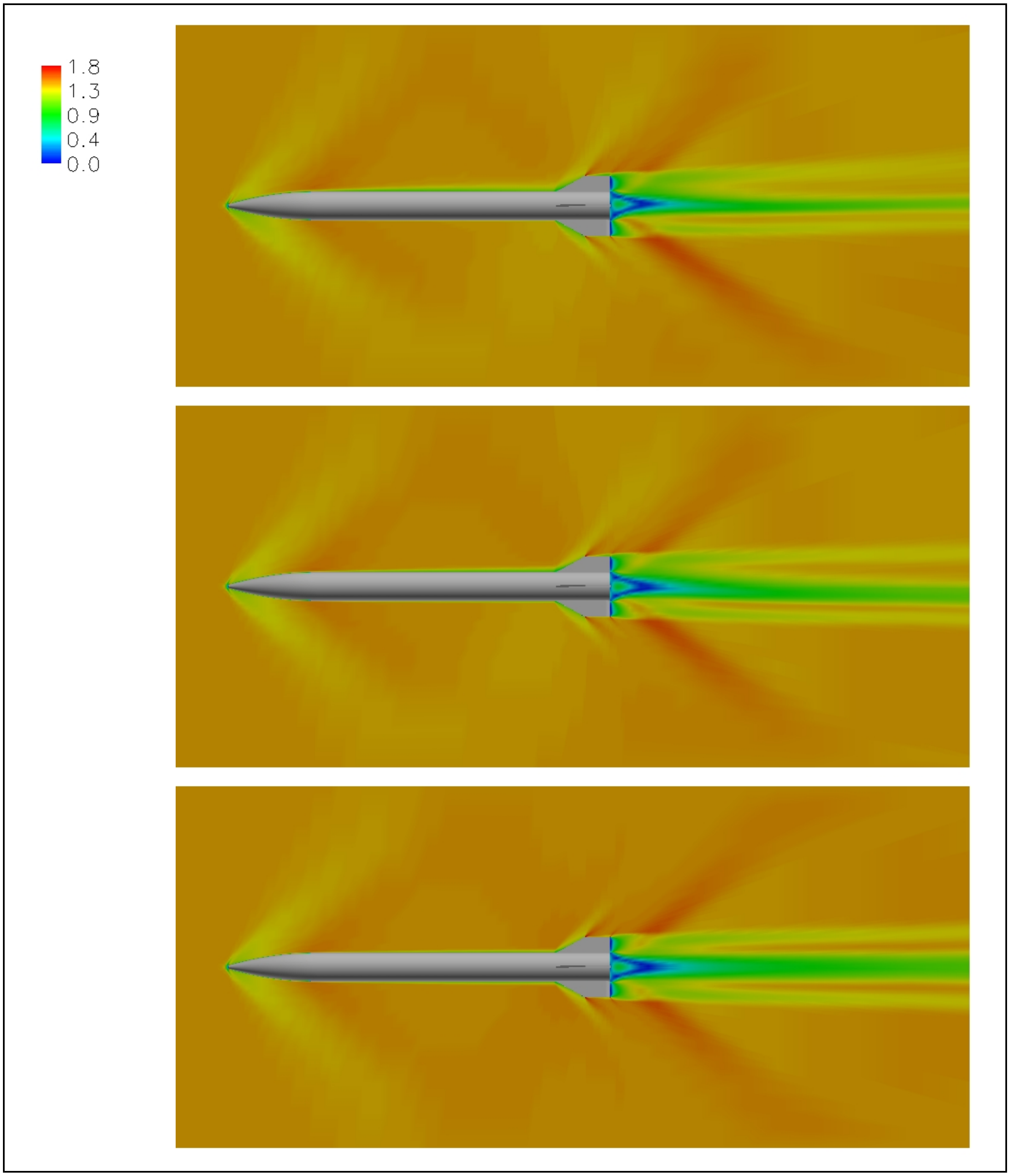

Figure 8. Mach contours for Mach number 1.5, alpha 0°, 2°, and 5° (bottom to top).

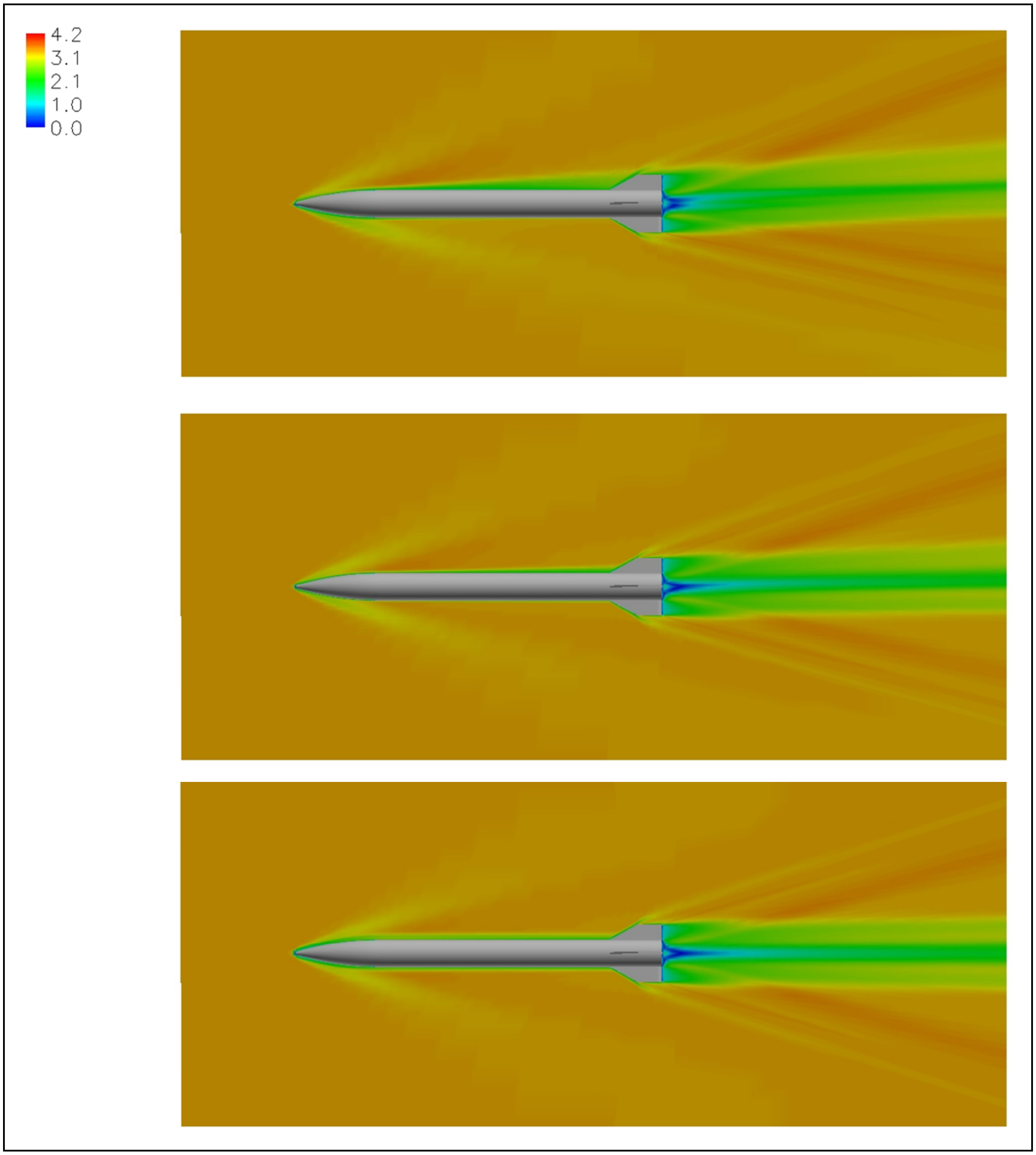

Figure 9. Mach contours for Mach number 3.5, alpha 0°, 2°, and 5° (bottom to top).

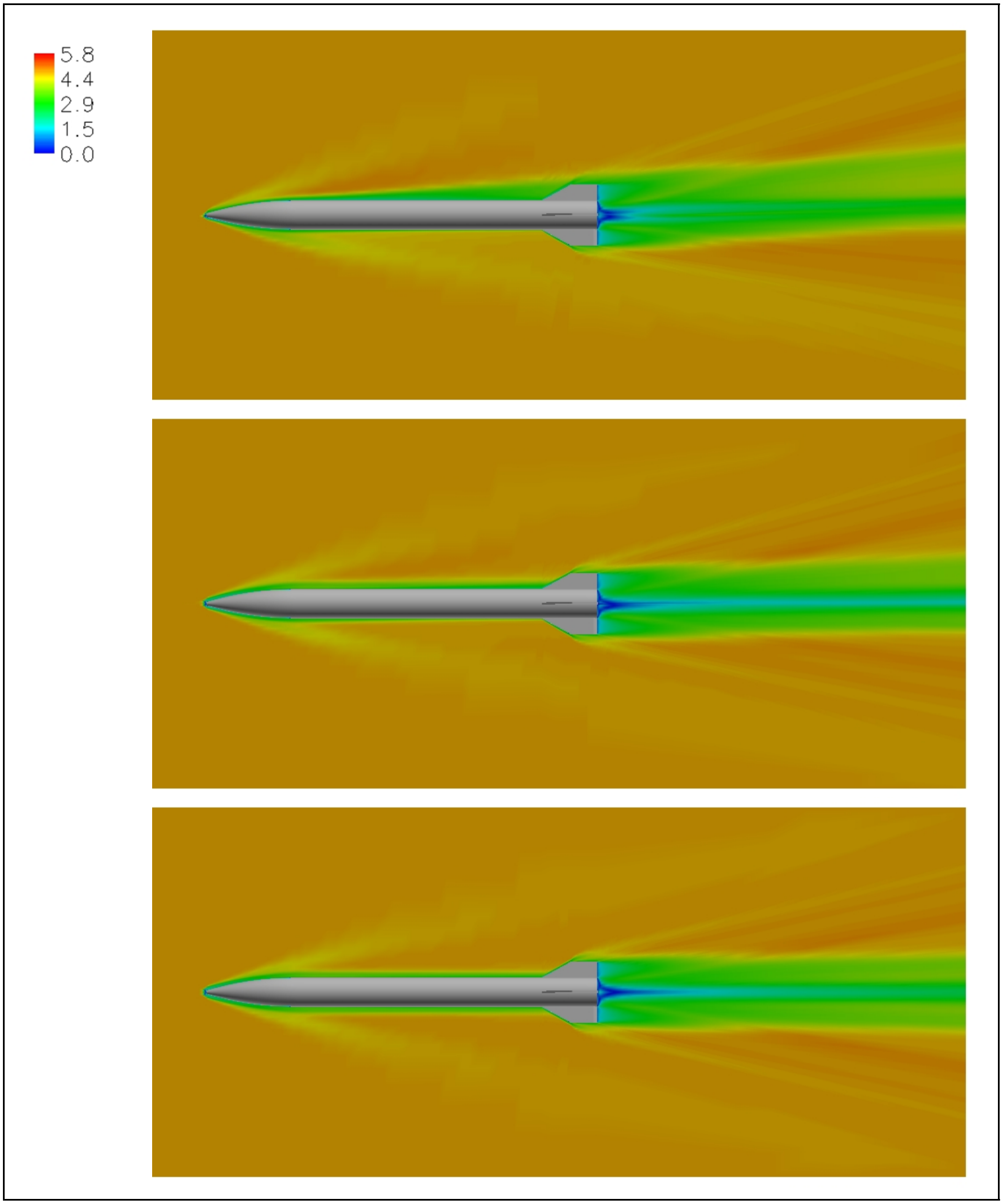

Figure 10. Mach contours for Mach number 4.85, alpha 0°, 2°, and 5° (bottom to top).

4.2 Quantitative Results

Force and moment data was extracted from the computed solutions using the tools available in the CFD++ software package (*11*). The data presented in table 1 represents the portion of that data considered in this study. This data is also presented graphically in figures 11–15.

Table 1. CFD++ force and moment data.

Mach Number	C_{Xo}	$C_{N\alpha}$	$C_{m\alpha}$	CPN	C_l
1.50	0.57222	10.35446	–37.55371	9.93533	–0.03938
1.75	0.55614	9.69340	–32.70878	9.68285	–0.02986
2.00	0.53689	8.87110	–27.04295	9.35694	–0.02367
2.20	0.51345	8.43842	–23.40816	9.08251	–0.02007
2.50	0.47540	7.78229	–18.70470	8.71200	–0.01606
3.50	0.37040	6.51906	–9.48703	7.76379	–0.00903
4.50	0.30187	5.97720	–6.02292	7.31616	–0.00580
4.85	0.28279	5.80373	–5.11673	7.19014	–0.00501
5.00	0.27606	5.76829	–5.08557	7.19015	–0.00471

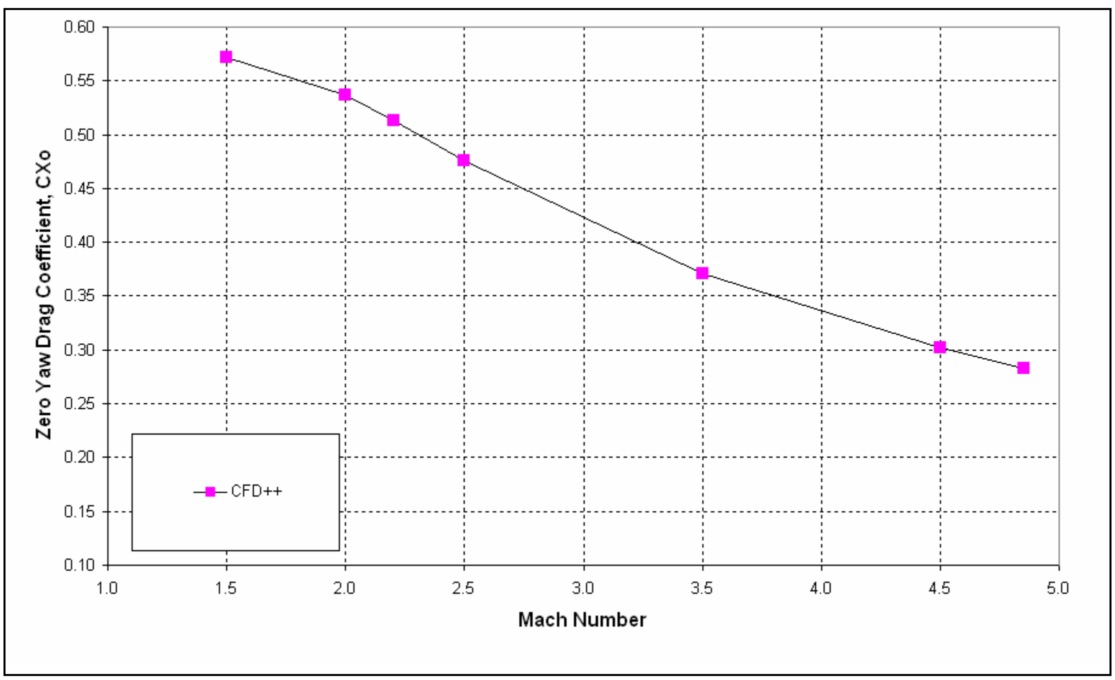

Figure 11. CFD++ results for zero yaw drag, C_{Xo}.

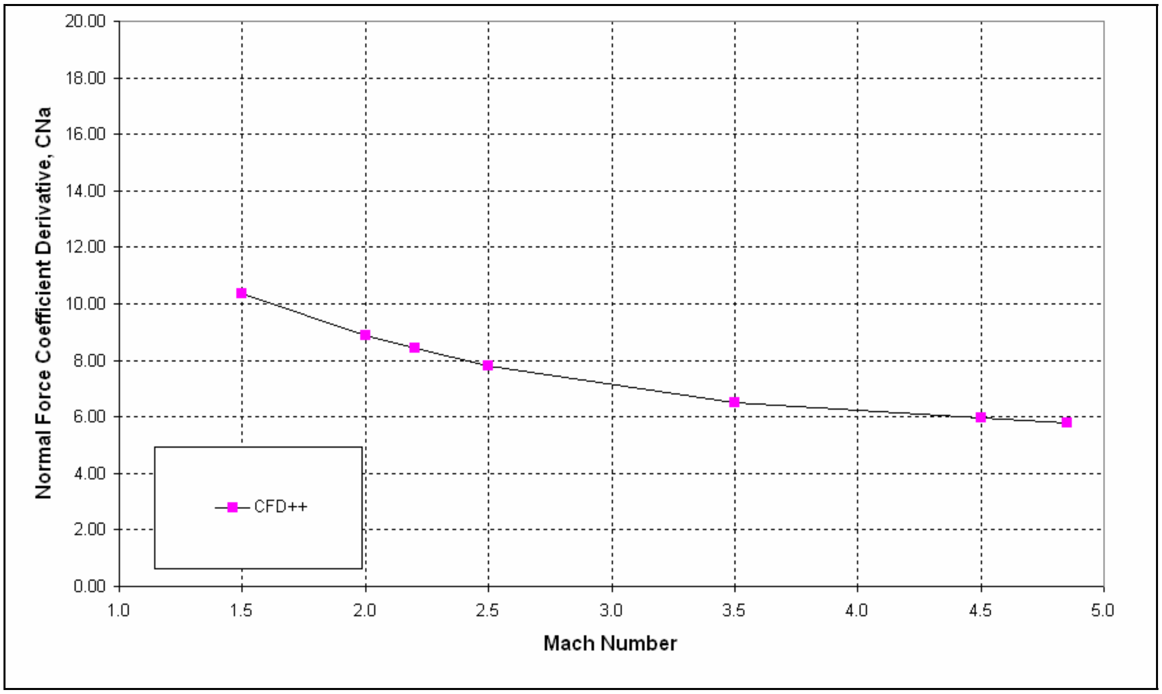

Figure 12. CFD++ results for normal force coefficient, $C_{N\alpha}$.

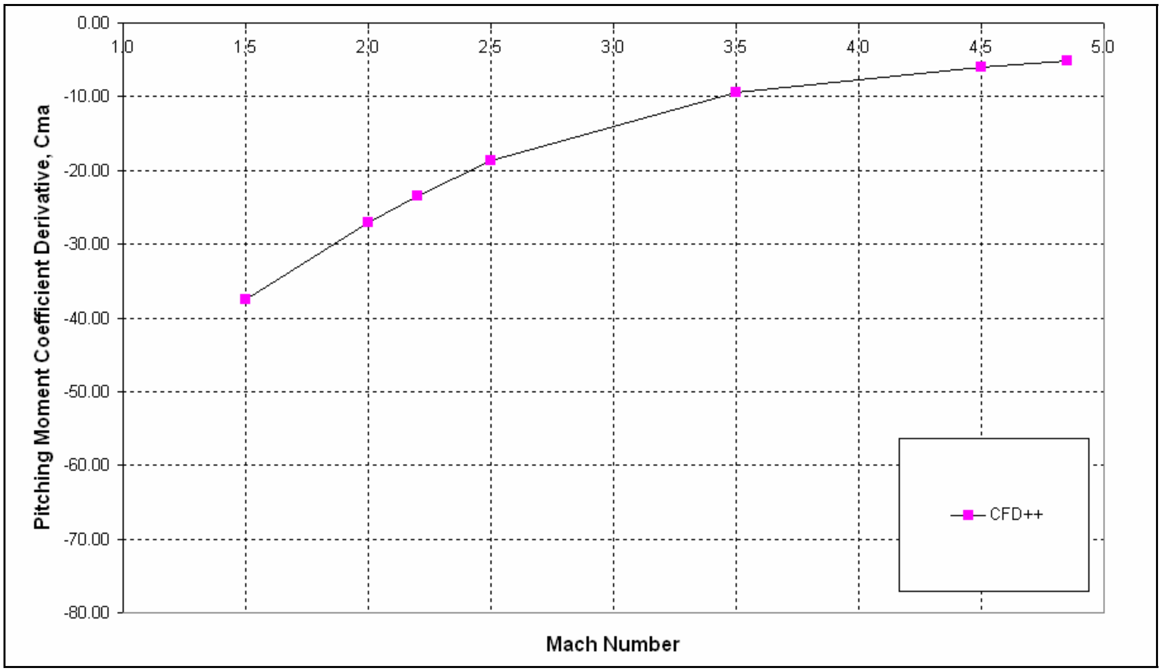

Figure 13. CFD++ results for pitching moment coefficient, $C_{m\alpha}$ (about center of gravity).

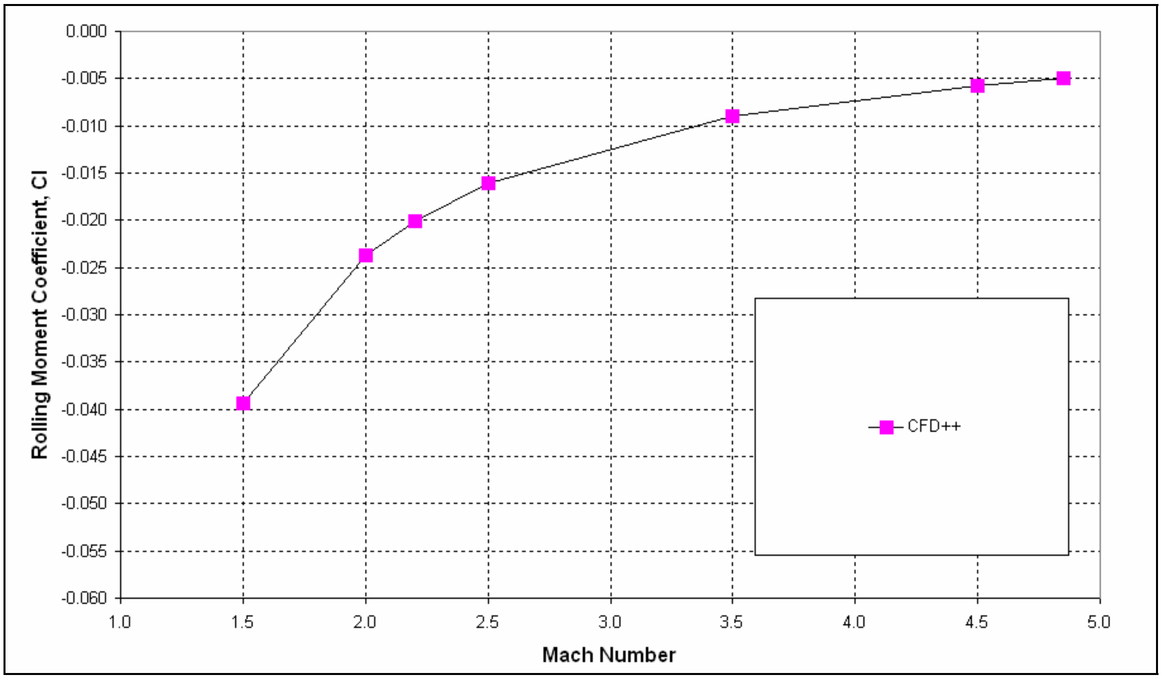

Figure 14. CFD++ results for rolling moment coefficient, C_l.

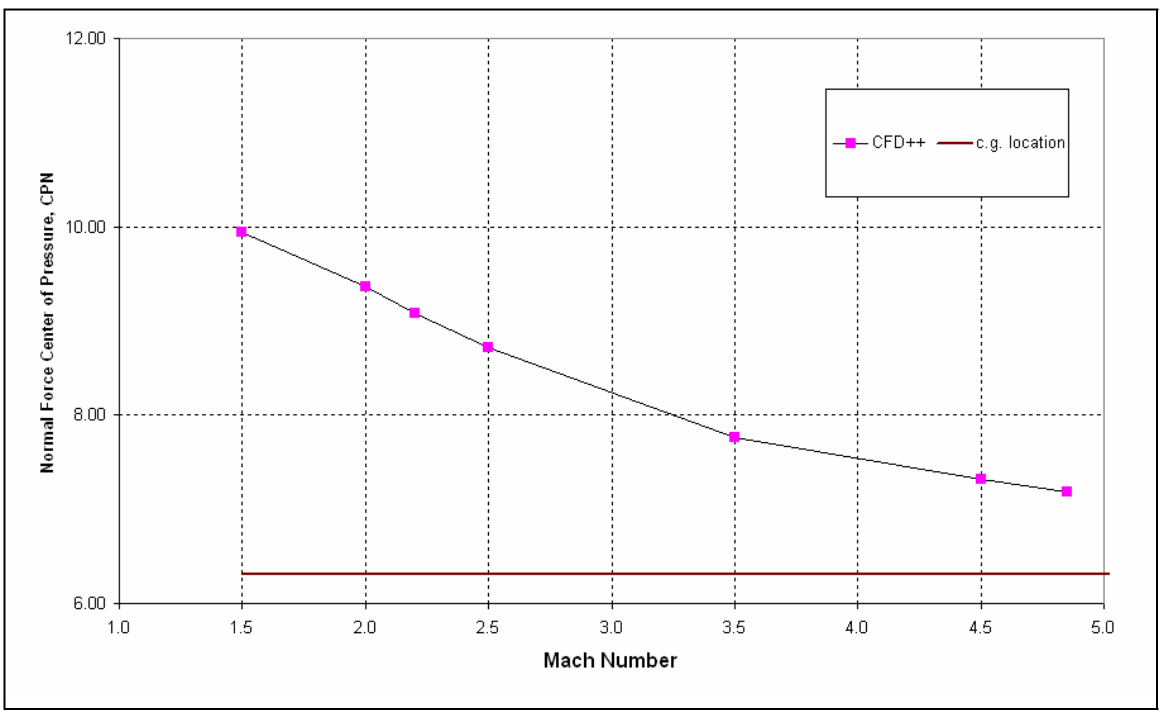

Figure 15. CFD++ results for normal force center of pressure, CPN.

Comparison of several force and moment variables is shown in figures 16–18. Given the results from the CFD++ computations, Arrow Tech Associates provided graphical comparison to the results of their semi-empirical analyses (*6*). There is good agreement for the variables presented—normal force, pitching moment and normal force center of pressure.

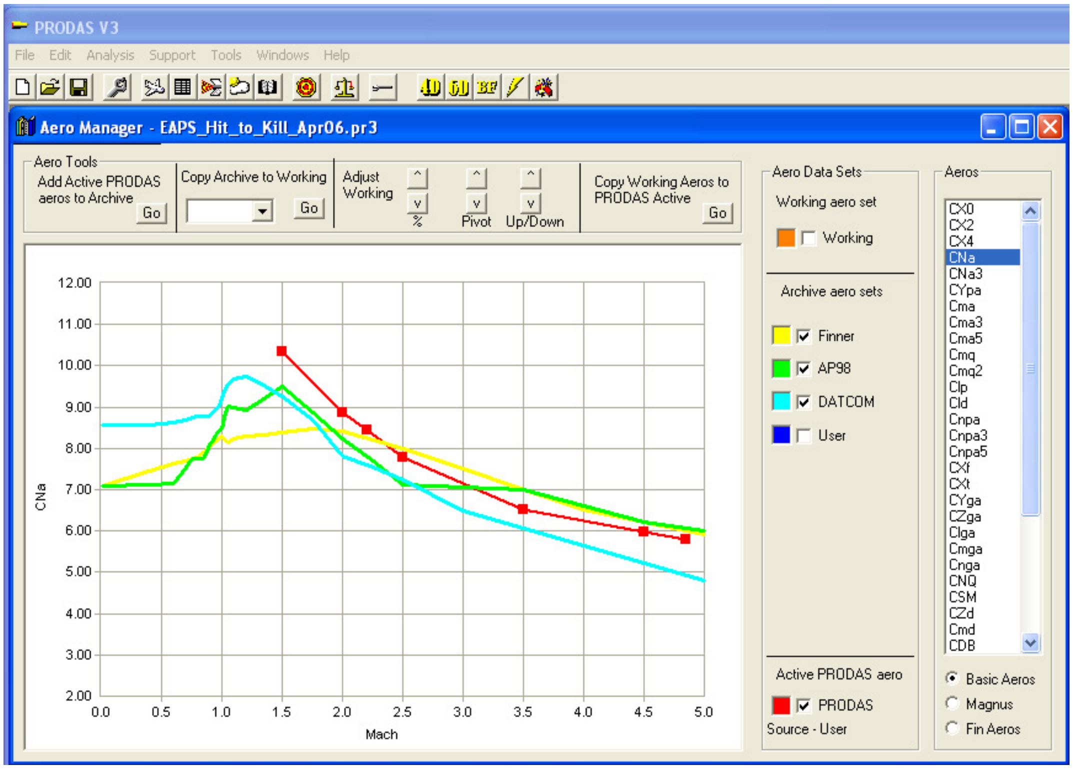

Figure 16. Comparison of normal force derivative.

5. Summary and Conclusions

Numerical computations using viscous Navier-Stokes methods were performed to predict the flow field and aerodynamic coefficients of a slender-body finned projectile configuration under atmospheric conditions. Full 3-D computations were performed. Computational results were obtained for this configuration at Mach numbers ranging from 1.5 to 5.0 and angles of attack from 0° to 5°, using a cubic k-ε turbulence model. Numerical results show the qualitative features of the symmetry plane for selected Mach number and angle of attack combinations. Force and moment data have been obtained from the computed solutions and found to match well with the available semi-empirical data for the configuration.

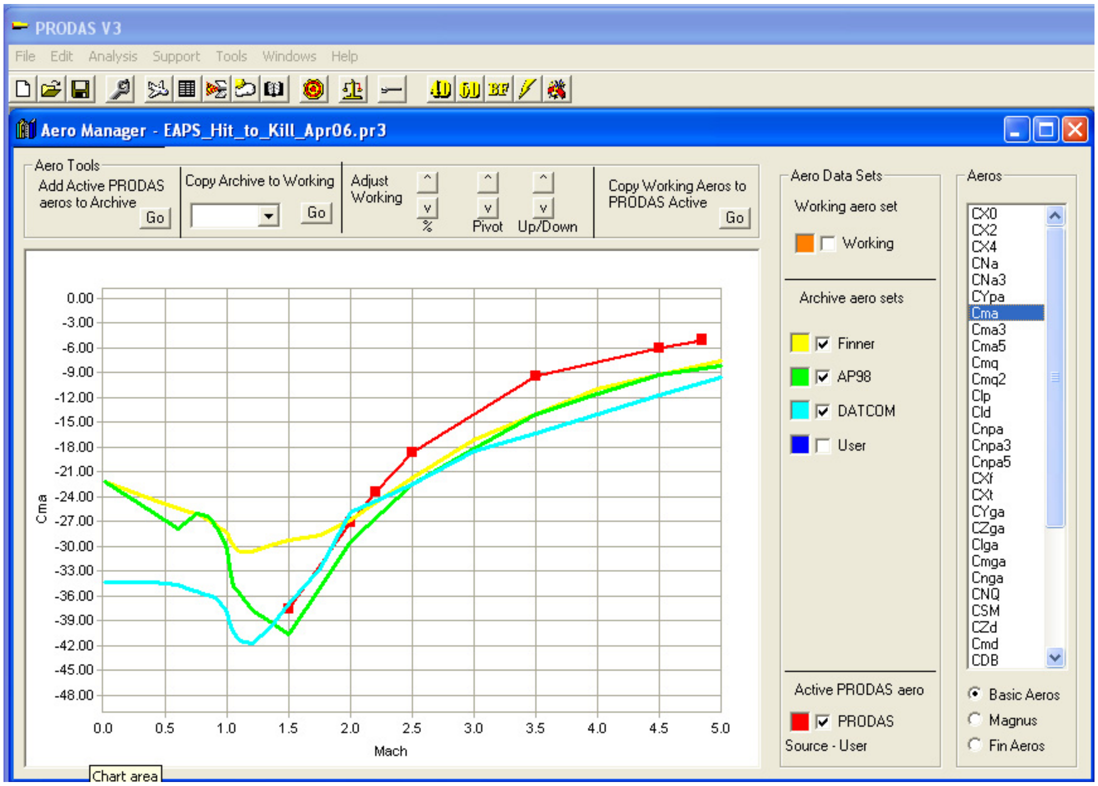

Figure 17. Comparison of pitching moment derivative.

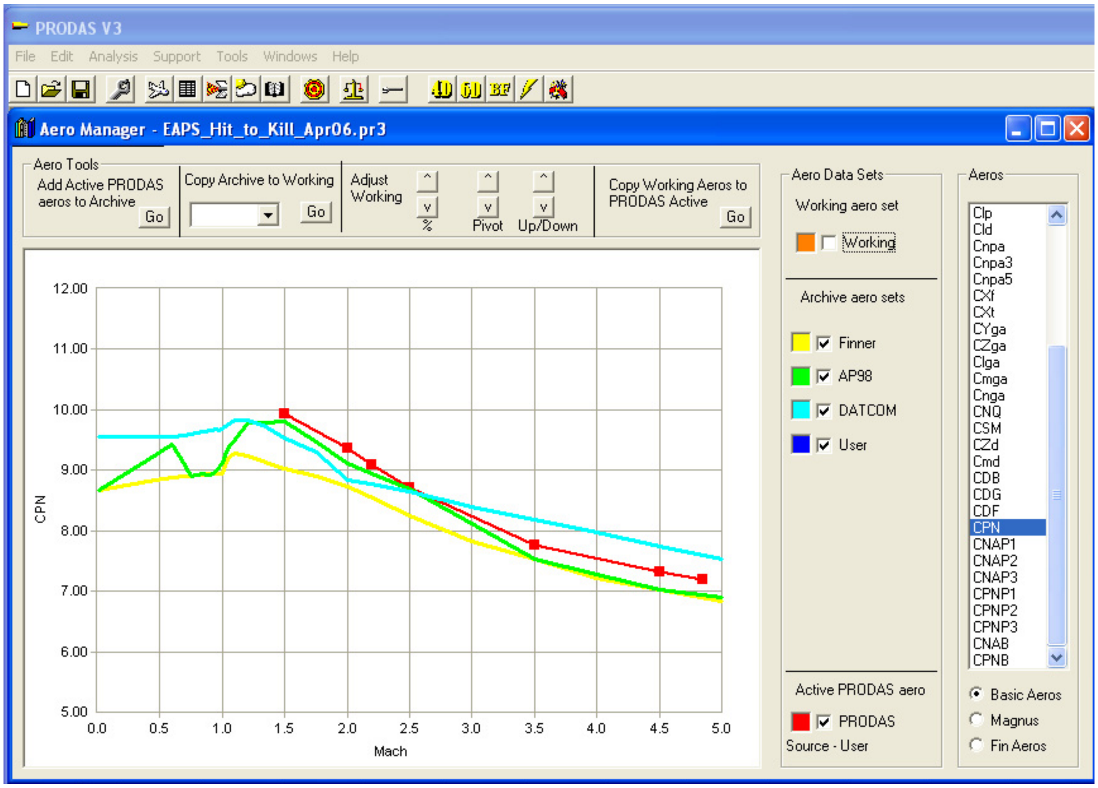

Figure 18. Comparison of normal force center of pressure.

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